The Influence of Towers and Conductor Sag on Transmission-Line Shielding

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THIS paper is the third of a sequence of papers intended to present data which may be used in determining the degree of protection from lightning obtainable by shielding transmission lines and structures with grounded overhead wires and masts. The first two papers of the sequence are: "Shielding of Transmission Lines,"[1] and "Shielding of Substations."[2]

Results Based on Earlier Model Tests

One sentence in the synopsis of a paper, "Lightning Protection for Oil Storage Tanks and Reservoirs,"[3] presented at the 1927 Pacific Coast convention of the AIEE, reads as follows:

"Tests show that excellent protection can be obtained by towers properly installed, but they do not indicate absolute immunity against hits."

The tests described in that sentence were laboratory tests on small-scale models. Using data obtained from those and other tests, a plan for protecting reservoirs by means of masts was developed. The integrity of those tests in indicating the protective value of shielding by grounded masts is well demonstrated. All oil reservoirs equipped with masts designed according to the data obtained from the tests described in that paper have been free from damage by lightning since the masts were erected during 1926 and 1927. In some installations, well-grounded masts only were used, and in others, where conditions indicated it advisable, the masts were supplemented by interconnecting overhead conductors.

In the 14 years which have elapsed since that method of protection was adopted for the oil reservoirs in question, many field data and many model tests have added to our knowledge of lightning and ways to guard against lightning damage. A bibliography of the reported work relating to this particular discussion was presented in the paper, "Shielding of Transmission Lines." One dictate of the knowledge obtained is that lightning protection for electrical transmission lines and other structures can be obtained most economically in any scheme of protection by taking advantage of the shielding effect of overhead ground wires and grounded masts located in proper juxtaposition to the objects to be protected. Since absolute protection for such structures is not usually economically practical, engineers desire statistical data which will enable them to determine the degree of protection provided by particular arrangements of overhead ground wires and masts. Such data must be obtained by many observations of actual lightning strokes and by careful model tests in the laboratory. The model tests must show valid correlation with field observations, and duplicate those characteristics of natural lightning which determine the paths taken by strokes. A full discussion of this topic appears in the first paper of the sequence.

Recent Model Tests

The first paper presented data showing the value of ground wire protection for a laboratory model representing a section of transmission line with a tightly-stretched conductor protected by a parallel tightly-stretched overhead ground wire. There was no appreciable sag in the section of model line tested, and no supporting towers were included within the test area.

The present paper gives the results of two check tests made in the California Institute of Technology high-voltage laboratory upon models identical with those used for two of the tests made at Trafford, and of further tests which determine the shielding effect, additional to that of overhead ground wires, provided by the transmission towers and conductor sag. Correction factors are given by means of which shielding data for parallel wires can be modified to account for the additional protection resulting from the presence of transmission towers.

The large amount of published data relating to lightning, surge testing with models, and the correlation between field observations and model tests under various conditions, permits the writing of this paper without including any matter relating to the "mechanism of natural lightning," and with little reference to the "fundamentals of model tests."

In keeping with conclusions of other experimenters, and the experience of the authors, it was considered justifiable for these tests to duplicate as closely as possible the test conditions used in obtaining the data for the first paper.

Laboratory Model and Test Conditions

The 2,000,000-volt 0.065-microfarad surge generator, built by graduate students at Pasadena, was used as the voltage source for the work of this report.

The conventional surge-generator circuit, with a resistance in parallel with the

Table I. Distribution of Stroke Terminations to a Typical 1,000-Foot Transmission-Line Span (Per Cent)

Model Arrangement	Conductor	Ground Wire	Tower	Ground Plane
(a) Taut wires only	23.4	58.5		18.1
(b) Tower, taut wires	18.7	50.1	12.7	18.5
(c) Tower, sagged wires	8.9	44.6	15.8	30.6

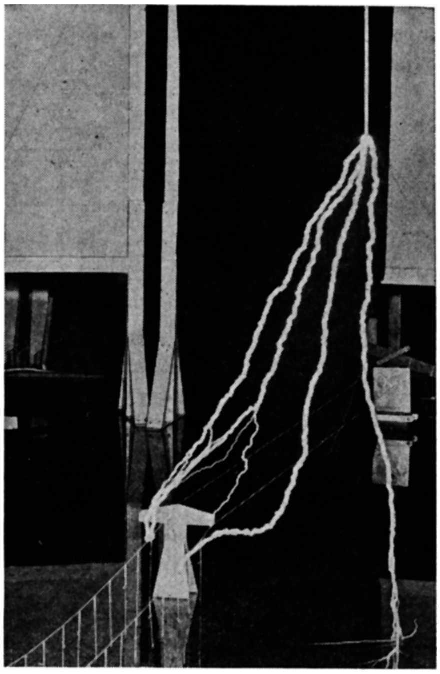

Figure 1. Model transmission line with wires sagged

Four strokes are shown

Paper 42-37, recommended by the AIEE committee on power transmission and distribution for presentation at the AIEE winter convention, New York, N. Y., January 26–30, 1942. Manuscript submitted November 24, 1941; made available for printing December 11, 1941.

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The authors acknowledge the assistance of E. A. Bureau, University of Kentucky, the several graduate students who assisted in making observations, and the National Youth Administration.

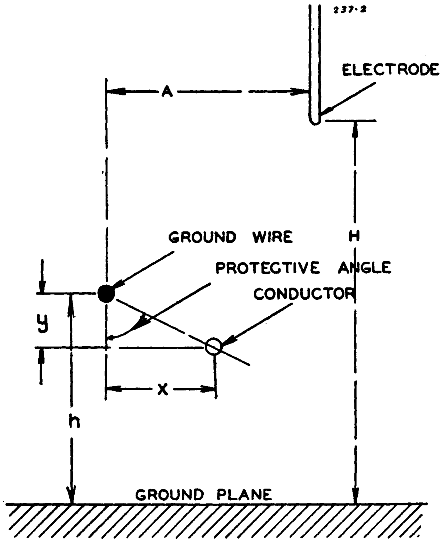

Figure 2. Taut ground wire and conductor parallel

Used to obtain data for Figures 3 and 4

test gap, was used. The wave form was approximately a $1^1/_2$- by 40-wave; and all strokes were fired at the minimum arc-over voltage of the test gap, with cloud electrode polarity positive. The discharge electrode was a $^3/_8$-inch diameter rod with a rounded end, mounted vertically with its lower end 50 inches above the ground plane of the model. The ground plane was a large salt water basin in which was submerged a grid of ground wires, covering the entire area of the basin and providing a 12-inch mesh over the test area. Conductors and tower used in the model were solidly grounded.

The model represented 100-foot transmission towers supporting 1,000-foot

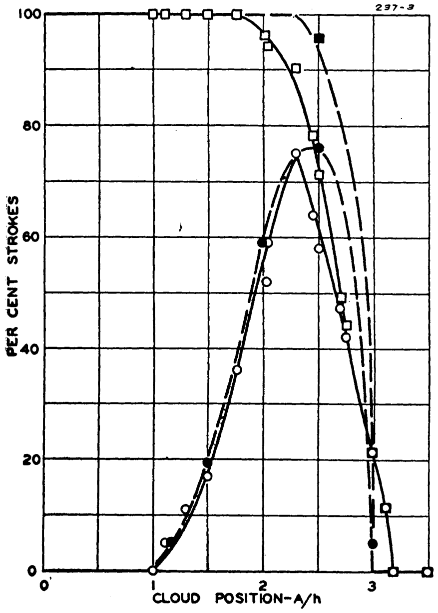

Figure 3. Check tests

$y/h \neq 0.1$. Solid curves Pasadena test data. Dotted curves Trafford data

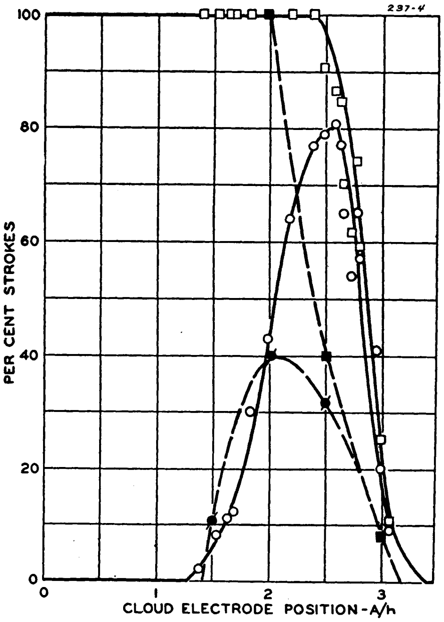

Figure 4. Check tests

$y/h \neq 0.2$. Solid curves Pasadena test data, Dotted curves Trafford data

spans, built to a scale of 10 inches = 100 feet (see Figure 1). Only one mode lscale was used, because experience has demonstrated that change in model scale does not change the relations of test results.[1] For test purposes, number 14 bare copper wire was used for overhead ground wire and conductor. For tests with sagged wires, the proper catenary was maintained by use of nonconducting anchor cords kept dry by having their lower ends attached to metal hooks just above the water.

To the scale of 10 inches = 100 feet, the equivalent height of the cloud electrode was 500 feet. This is the generally recognized minimum height of cloud from

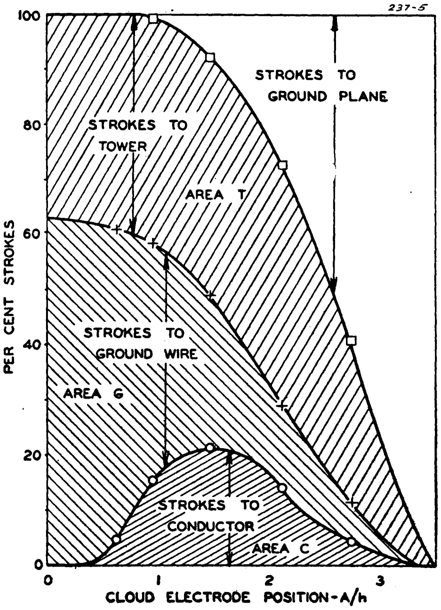

Figure 5. Explanation of distribution curves

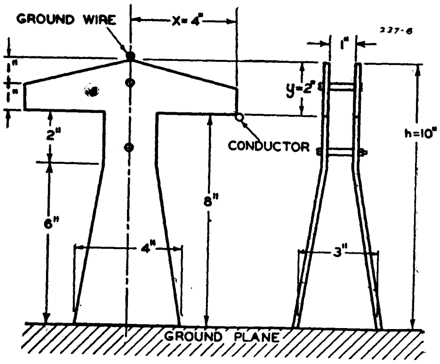

Figure 6. Detail of model tower

Scale 10 inches = 100 feet

which lightning develops. This arrangement gives conservative results for shielding conditions. The first paper included a study of the effect of protective angle between ground wire and conductor. One set of data was for an angle of 64 degrees. In that test, a measurable percentage of strokes terminated on the "protected line conductor." This 64-degree angle was chosen as a fixed reference angle and used throughout the tests reported in this paper.

Methods of Observation

In reporting the tests, the total number of strokes for any condition was divided into groups and classified according to the points of stroke termination. The strokes were designated as strokes to conductor, strokes to overhead ground wire, strokes to tower, and strokes to ground plane. At least 100 strokes were "fired" for each position of the cloud electrode. The points of stroke termination were recorded by two observers viewing the model from positions such as to have their lines of vision intersect perpendicularly at the point subject to test. This made it possible to determine accurately and without any difficulty the point of stroke termination. The observers exchanged positions after each 25 strokes. If results of the first 50 strokes were not consistent with those of the following 50 strokes, additional strokes were fired. The lack of dependence of results upon any unique skill or opinion of an observer is well established by the agreement in the reports of the 16 observers used during the series of tests.

Model Arrangements

Tests were made under three conditions:

1. As shown in Figure 2, using taut ground wire and conductor parallel to each other, without tower in place or conductor sagged. These were check tests to correlate this work with that reported in the first paper.

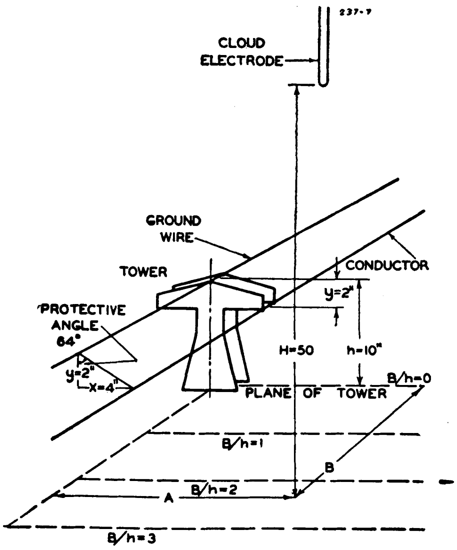

Figure 7. Taut ground wire and conductor parallel

Tower in place. For Figures 8–12, 22, and 24

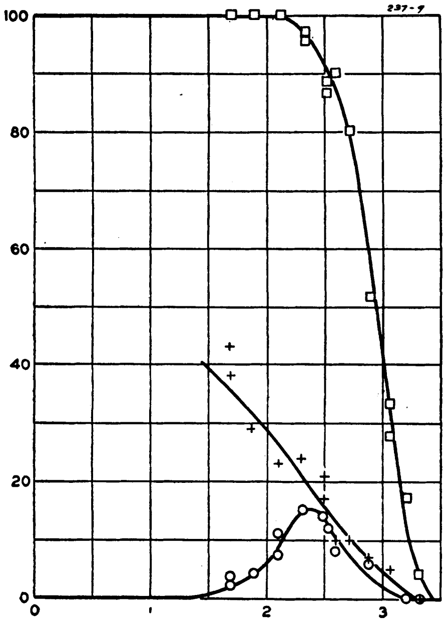

Figure 9

$B/h=0.5$

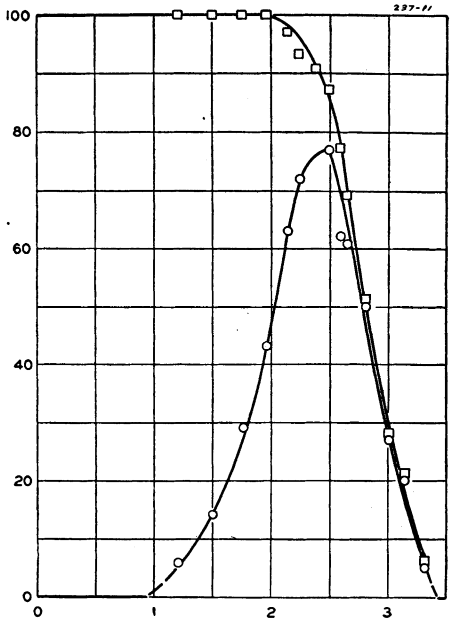

Figure 11

$B/h=2.0$

2. As shown in Figure 7, using taut ground wire and conductor with model tower installed to determine added shielding effect of tower.

3. As shown in Figure 13, using ground wire and conductor under less tension and suspended from model tower to simulate the sag that is always present for actual transmission-line conditions. Tests were made with this arrangement to evaluate the effect of line sag on shielding.

Results of Check Tests

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In the check tests, the wires representing the line conductor and the overhead ground wire were tightly-stretched copper wires supported outside the test area and without towers or line sag within the test area. The first check test was made with $h=10.0$ inches; $y/h=0.10$; $H/h=5$; protective angle 64 degrees (see Figure 2); and the second check test was made with the same arrangement except for a change in the ratio y/h from 0.10 to 0.20. Figures 3 and 4 show the comparative results of the tests made in the two laboratories. The Pasadena test results are plotted as solid-line test curves, and the Trafford test results as dotted-line test curves.

The results of the two check tests, while not in exact agreement with the Trafford tests, are as much in accord as one could expect for tests of this character made in different laboratories by different experimenters who have no agreement as to number of "shots" for each condition, and other plans of procedure.

The differences which are to be noted in the curves may be due to the difference in the number of strokes made to each point. The solid curves represent more than 1,500 strokes for each curve and a minimum of 100 strokes for each A/h value used in plotting the curve. However, in considering actual lines, the effect of line sag and towers is such as to more than make up for the difference in the two

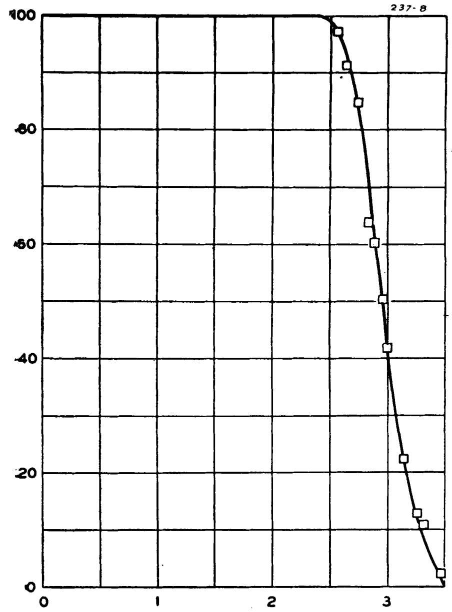

Figure 8. For cloud electrode in plane of tower

$B/h=0$

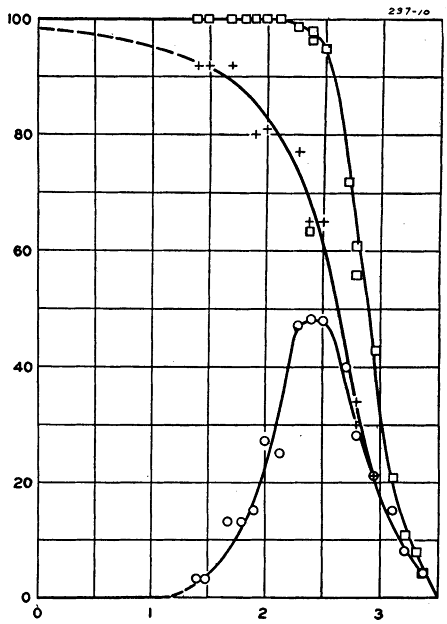

Figure 10

$B/h=1.0$

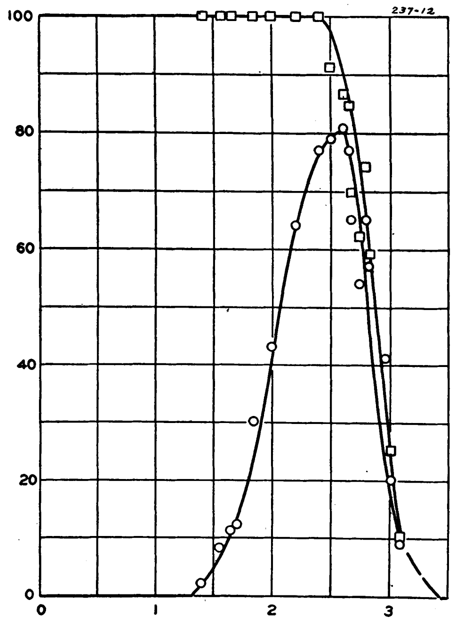

Figure 12. Tower removed

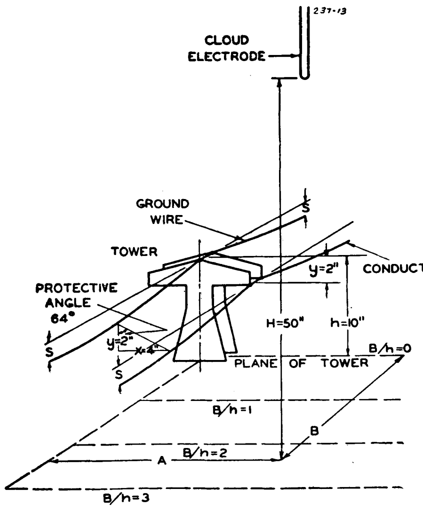

Figure 13. Sagged ground wire and conductor parallel

Tower in place. For Figures 14–20 and 23

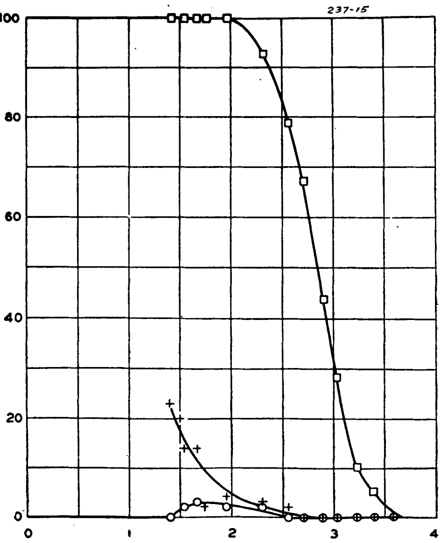

Figure 15

B/h=0.5

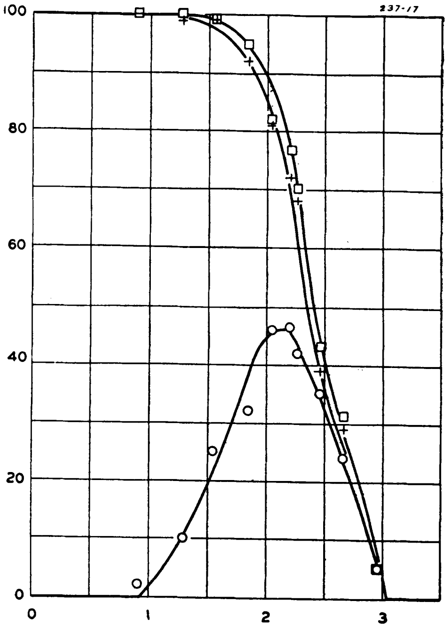

Figure 17

B/h=2.0

curves. One result of the comparison just made is the indication that it is well in making surge tests of the character under discussion to base findings on results obtained by making at least 100 "strokes" for each plotted point. See Table II.

Shielding Effect of Towers

The data obtained with towers in the model line added to our general realization of their value as aids in line shielding by providing data which show that, for a cloud electrode at five times tower height above ground, a line conductor suspended below a metallic cross arm is completely protected from strokes originating from a cloud point in a plane through the tower and perpendicular to the line. The data also show that the protection furnished by the tower decreases with distance from the tower measured along the line, as follows:

With 100 per cent protection at the tower, there is only 85 per cent protection with the cloud point moved parallel to the line a distance of one-half tower height from the tower. If the distance from the plane of the tower to the point of cloud discharge is equal to a full tower height, the protection is only 50 per cent. The towers offered no protection to the line conductor against strokes originating from a cloud point more than two times tower height along the line from the plane of the tower (see Figure 22). Towers 100 feet high and spaced 1,000 feet apart in a transmission line reduce the number of probable strokes to the conductor for the over-all line to 80 per cent of the number that would be expected for a section of line without towers. The line conductor and overhead ground wire were kept taut without appreciable sag in these tests (see Figure 7).

Shielding Effect of Line Sag

The third set of tests on the model line was made with the tower in place and with line conductor and overhead ground wire kept parallel to each other, both being sagged 40 per cent of the tower height at the center of the span (see Figure 13). These tests show that with 100-foot towers 1,000 feet apart, the number of strokes that hit the conductor for the cloud

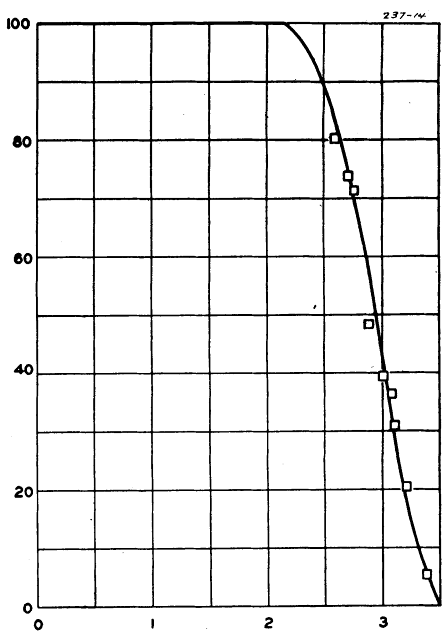

Figure 14. Cloud electrode in plane of tower

B/h=0

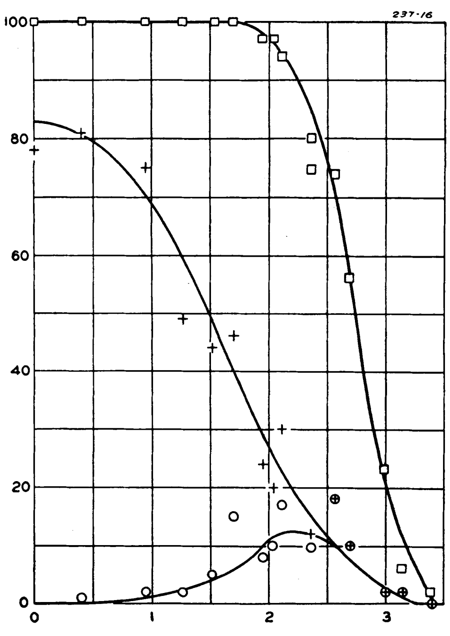

Figure 16

B/h=1.0

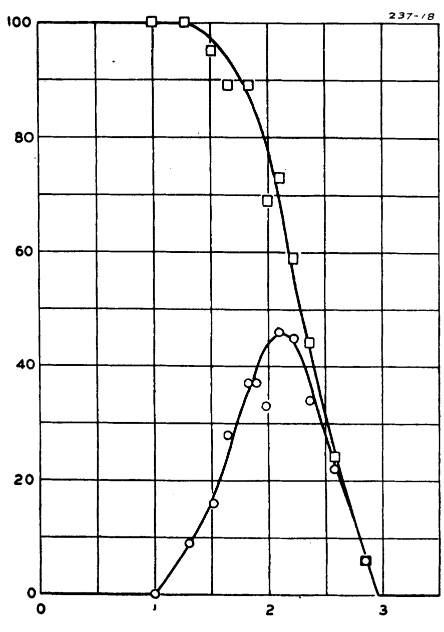

Figure 18

B/h=3.0

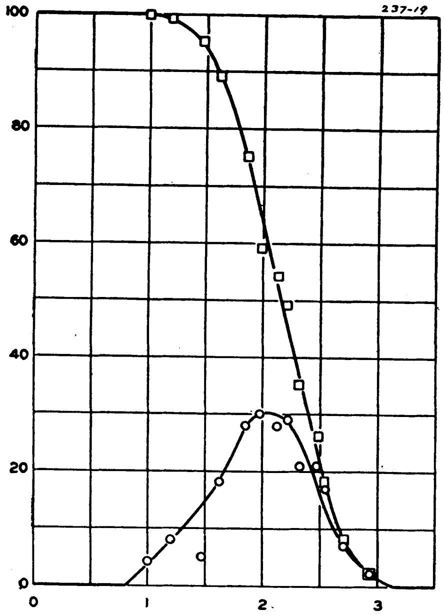

Figure 19

$B/h = 4.0$

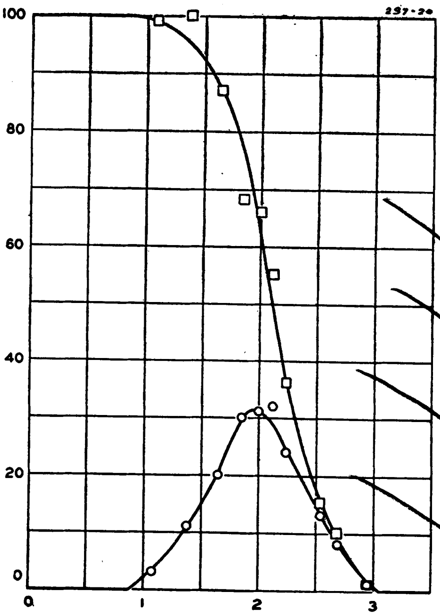

Figure 20

$B/h = 5.0$ 8·871

electrode opposite the center of the span was only 38 per cent of the number observed when the lines were not sagged. For a uniform distribution of strokes originating from clouds along the line, the line sag reduced the number of strokes to conductor to 52 per cent of the number obtained when towers were in place but there was no line sag (see Figure 23).

Distribution of Strokes

Tests involving thousands of strokes to the model-line area from a minimum cloud height of five times the tower height showed that the line is immune to strokes that originate along the line, outside a band, the width of which is about seven times the tower height. Table I presents the distribution for strokes originating from the cloud electrode located above the line at points uniformly distributed within a band having a width of seven tower heights and with its axis parallel to the axis of the transmission line.

Explanation of Figures

Figures 2 to 24, showing model arrangement and results of tests, enable ready comparison of results. In these diagrams:

h = Height of tower and ground wire at point of tower support. In tests this model was always 10 inches high.
y = Vertical component of displacement of conductor below ground wire.
x = Horizontal component of displacement of conductor from ground wire.
$/P$ = Protective angle = $\tan^{-1} x/y$. 6.5/9
H = Height of lower end of cloud electrode above ground plane = 50 inches.
A = Horizontal component of displacement of cloud electrode *normal* to the line, measured from ground wire.
B = Horizontal component of displacement of cloud electrode *parallel* to the line, measured from center line of tower.
s = Sag of ground wire and of conductor at center of span, from heights at tower support points.

For each of the three tests, all model dimensions were fixed, except the horizontal displacement of the cloud electrode, given by A and B, which was varied throughout the region from which strokes might terminate on the model line.

Figure 5 explains the curves of test results. For each value of A/h, the percentage strokes to conductor are shown by the ordinate to the lowest curve, test points shown by ⊙; the percentage to ground wire by the difference between the ordinate of the curves whose points are (+) and the curve whose points are ⊙; the percentage strokes to tower by the differences between the curves whose points are (□) and the curve whose points are (+). Strokes to ground plane are represented by the difference between the 100 per cent ordinate and the curve whose ordinates are marked by (□).

Figure 2, shows arrangement of model line with taut wires only.

Figure 3 shows results for $y/h = 0.1$, and Figure 4 results for $y/h = 0.2$ for tests at both laboratories, with wires only as shown in Figure 2. Figures 5 and 6 are the explanatory curve and detail of model tower, respectively.

Figure 7, shows arrangement of model line with tower in place and taut wires.

Figure 8 shows stroke distribution for electrode at various positions (A/h) in the plane of tower ($B/h = 0$).

Figure 9 shows stroke distribution for electrode at various positions (A/h) in the

Table II. Typical Test Observation Data

	Test 89—Tower, Taut Wires, 5 Strokes in Each Group, $y/h = 0.2$; $B/h = 1.0$; $A/h = 2.40$ — Stroke Distribution				Test 149—Tower, Sagged Wires, 5 Strokes in Each Group, $y/h = 0.2$; $B/h = 1.0$; $A/h = 2.36$ — Stroke Distribution			
	Tower	Ground Wire	Conductor	Ground Plane	Tower	Ground Wire	Conductor	Ground Plane
	1	3	1	0	4	0	0	1
	2	1	2	0	3	0	0	2
	3	1	1	0	3	0	0	2
	0	0	5	0	4	0	0	1
	1	1	3	0	5	0	0	0
	2	0	3	0	2	0	1	2
	1	0	4	0	3	0	1	1
	1	2	2	0	3	0	1	1
	0	2	3	0	3	0	2	0
	3	0	1	1	2	0	2	1
First 50 Strokes	28%	20%	50%	2%	64%	0%	14%	22%
	4	0	1	0	3	0	2	0
	1	1	3	0	2	1	1	1
	2	1	2	0	3	0	0	2
	2	1	2	0	4	0	0	1
	1	2	2	0	3	0	1	1
	1	0	4	0	1	0	2	2
	1	1	2	1	4	0	1	0
	2	0	3	0	2	0	1	2
	3	0	1	1	5	0	0	0
	1	1	3	0	4	0	1	0
Second 50 Strokes	36%	14%	46%	4%	62%	2%	18%	18%
100 Strokes	32%	17%	48%	3%	63%	1%	16%	20%

5-6 6/7 Table

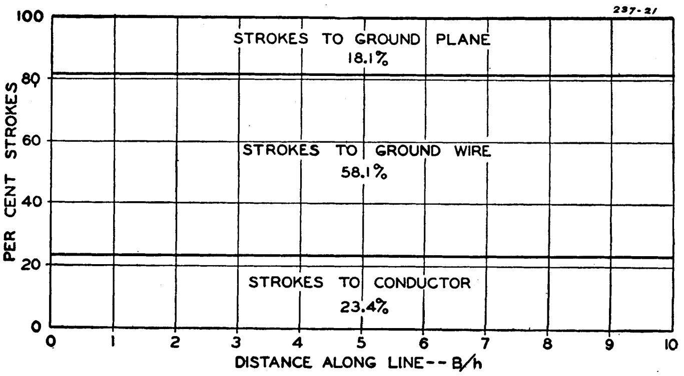

Figure 21. Distribution of strokes along line

Taut parallel ground wire and conductor only

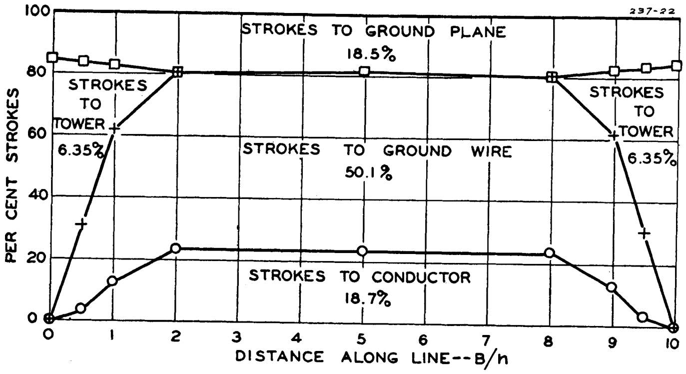

Figure 22. Distribution of strokes along line

Taut parallel ground wire and conductor with towers in place

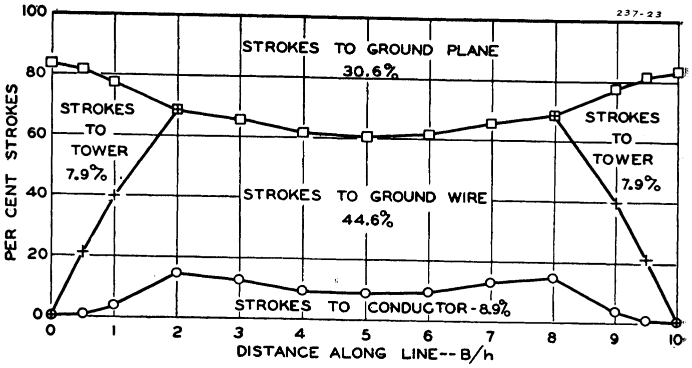

Figure 23. Distribution of strokes along line

Sagged parallel ground wire and conductor with towers in place

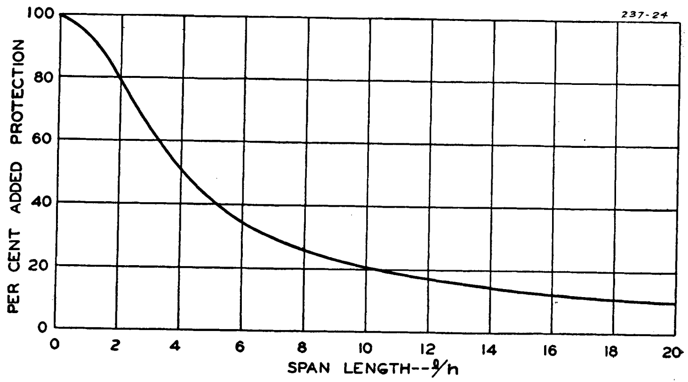

Figure 24. Added protection resulting from presence of towers, for various lengths of span

plane one-half tower height away from tower ($B/h=0.5$).

Figures 10, 11, and 12, show stroke distribution for $B/h=1.0$; for $B/h=2.0$; and with tower removed, respectively.

Figure 13, shows arrangement of model line with tower in place and 40 per cent sag in wires. Figures 14 through 20 show stroke distribution for electrode at various positions A/h in planes for values $B/h=0.0$; 0.5; 1.0; 2.0; 3.0; 4.0; and 5.0.

Interpretation of Test Data

The areas C, G, and T, bounded by the curves, as illustrated in Figure 5, show values of stroke distribution to conductor, to ground wire, and to tower, integrated for all values of A/h. The remaining area shows strokes to ground plane for integrated values of A/h up to about 3.5 times tower height.

Figures 21, 22, and 23, in columns 1, 2, and 3, respectively, show the distribution of strokes along the line, where B/h measures distance from tower in terms of tower height (h). The ordinates of these curves for each (B/h) value were obtained from the areas of the preceding curves. The areas of Figures 21, 22, and 23 show the distribution for stroke terminations for an entire span. The data for Table I were obtained by measuring these areas.

Figure 24, derived from data for Figure 22, shows as a function of span length the percentage of added shielding provided by towers. For a 40 per cent sag in a 1,000-foot span, a similar curve could be drawn showing the added shielding effect of towers and sag. This has not been done because in actual practice sag changes with tower spacing and conductor tension.

Conclusions

The tests on which this report is based show that the Wagner, McCann, and MacLane protection values are conservative, because they do not include the protection provided by towers and line sag. The preceding curves can be used to determine the additional protection due to towers and conductor sag for a protective angle of 64 degrees. For other protective angles estimates of the added protection can be based on reasonable interpretation of these results. The magnitude of this added protection is important, since for typical spans it shows an increased protection of 20 to 80 per cent.

Appendix

Figure 25 is included in this paper to call attention to the pattern formed in the grounding pool, apparently on the surface of the water. At the time this picture was made, the water had a somewhat higher resistance than was used during the regular testing program. Figure 1 was made after the addition of more salt to the water. The "crowfoot" figures were then less noticeable. Figure 8 in the paper, "Lightning Protection for Oil Storage Tanks and Reservoirs"[3] showed the spread of discharge current over a concrete floor. The "crowfoot" travel of current over that floor made a photograph much like the ones shown in this paper. These pictures are of interest in showing what may happen when large currents arrive at a point of sudden change in resistance. The resistance of the concrete floor was very high.

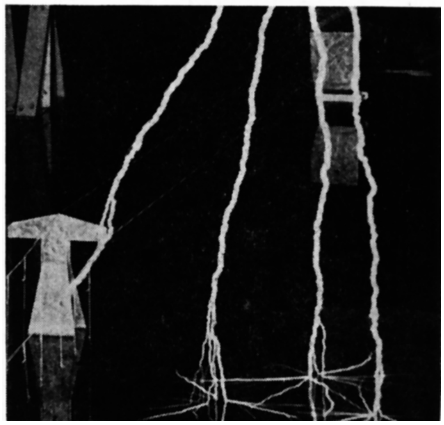

Figure 25. "Crowfooting" or spreading of streamers on surface of abnormally high-resistance water plane